Proceedings of the International Mechanical Engineering Congress & Exposition
IMECE 18
November 9-15, 2018, Pittsburgh, Pennsylvania, USA

IMECE2018-86726

TORCH END-EFFECTOR AND TIG ELECTRODE CHANGEOUT DESIGN FOR A TIG WELDING ROBOT USED IN METAL BIG AREA ADDITIVE MANUFACTURING

Christopher Masuo, Andrzej Nycz, and Mark W. Noakes
Manufacturing Demonstration Facility
Oak Ridge National Laboratory
Knoxville, Tennessee, USA

Jared Bell, Justin Killian, Chandler Oakley, and William R. Hamel
University of Tennessee
Knoxville, Tennessee, USA

ABSTRACT

Metal Big Area Additive Manufacturing (mBAAM) is a promising approach to large-scale metal additive manufacturing (AM) or 3D printing. The mBAAM system uses an arc-based wire-fed welding robot to build metal parts. A multi-degree-of-freedom robotic arm is known for its extensive range of motion and reliable tool handling. Attaching a torch end-effector to a robotic arm gives it welding capabilities; however, this decreases the motion range and dynamics of the robot. As a result, build volume and printing accuracy are decreased. Additionally, only a portion of time is spent printing in an arc-based process. Maintenance leads to downtime on the system. In a tungsten inert gas (TIG)-based process, the torch electrode wears out over time and must be changed to avoid defective deposition. This paper proposes an approach for a compact torch end-effector to improve the robot's build volume. This paper also proposes an approach to reducing non-printing process time by designing and implementing a semi-automated electrode changing system.

Keywords: Metal Big Area Additive Manufacturing; 3D Printing; Robotic Welding Arm; Electrode Changeout Design; Torch End-Effector Design

INTRODUCTION

In traditional manufacturing, the fabrication of large, complex metal structures is expensive and time consuming. It requires a tremendous amount of planning and uses multiple machine processes to create an object out of a large, metal block. In additive manufacturing (AM), objects are created by placing material in a layer-by-layer process. A 3D generated CAD (computer-aided design) model of the object and an understanding of the AM machine is required to build a part, which is simpler than the processes of traditional manufacturing [1]. AM methods for manufacturing metal objects can be fulfilled by powder-bed or direct energy deposition (DED) systems [2]. Objects built by a powder-bed system are typically small, having a build volume of $0.03m^3$ [2], [3]. With DED system, processes can either involve the use of laser, electron beam, or arc welding [2]. Compared to the other processes, arc welding has a higher deposition rate, and is much cheaper than laser-based systems, which is suitable for large-scale production. Build volume can also be expanded by using a robotic arm. This leads to a process known as wire and arc additive manufacturing [4-8], and in large-scale, it is known as Metal Big Area Additive Manufacturing (mBAAM).

mBAAM can be achieved by gas tungsten arc welding (GTAW) or gas metal arc welding (GMAW). In GMAW, a filler wire electrode creates an arc on the work object, generating heat and melting the wire. In GTAW, also known as tungsten inert gas (TIG) welding, a non-consumable tungsten electrode creates an arc and melts filler wire to produce deposition. This allows precise control of the heat input, while not affecting the arc length [8]. This creates smoother deposition, which can be useful in mBAAM. The mBAAM TIG system addressed in this paper was developed at the Manufacturing Demonstration Facility of Oak Ridge National Laboratory.

The mBAAM system (Fig. 1) consisted of a Mitsubishi PA10-7CE seven degree-of-freedom robotic arm, a Miller Dynasty 350 TIG welder, a CK Worldwide water-cooled torch, a CK Worldwide WF-5 wire feeder, and pyrometers [9]. The initial prototype was a success, but improvements could be made. Production speed is a key factor in industry. High deposition rates result in faster builds, but large objects can still take many hours to complete. To prevent overheating, a water-cooled torch is necessary. A standard water-cooled torch for GTAW is typically 229mm long. Therefore, this standard size was used in the mBAAM system. An end-effector allowed the PA10 system to carry the torch, but it led to increasing the end effecter tip standoff to 267mm. Increasing the length and size of the end-effector reduced the effective workspace of the manipulator and increased the risk of the arm colliding with objects [10]. Lengthy end-effectors can also restrict the arm's position, which limits the part size geometry. Additionally, more mass is introduced at the robot's end, which results in higher inertia. This can strain the arm and decrease its movement precision. A known problem in GTAW is the wire feeding direction. Limited adjustability results in gap defects causing possible build errors [8].

A new torch had to be selected and a small, compact torch end-effector had to be designed to fix these potential problems using the following objectives:

- Minimize torch end-effector length
- Minimize mass
- Similar/same performance as the original torch
- Wire feed guide adjustability

Automation is also a key factor to increasing productivity. A TIG torch consists of a cup/nozzle, collet body, collet, insulator, torch body, and a back cap (Fig. 2). Tungsten electrodes are inserted in the torch where the collet clamps/unclamps it in place by twisting the back cap. The original procedure to change electrodes was done manually. Manually changing the electrodes was slow because the previous end-effector design made it difficult to access the back cap as seen in Fig. 3. The system also had to be fully stopped to ensure safety of the operator. Automation of this tedious and cumbersome process was desired to improve the productivity and efficiency of the mBAAM TIG system. Excluding human presence also minimized safety concerns. Therefore, an electrode changeout system (ECS) separate from the robot arm was designed with the following objectives:

- Accommodate the new short torch to increase build volume
- Easy interface with new end-effector design
- Reliable automated electrode removal and replacement
- Simplistic control scheme for automation

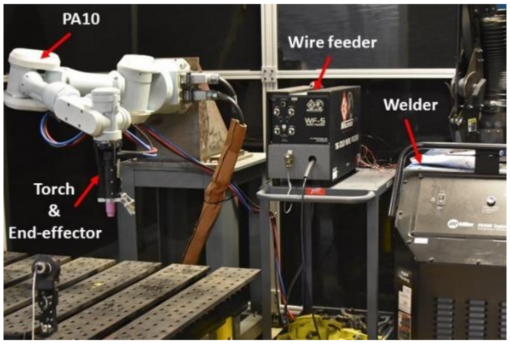

Figure 1. Original mBAAM system.

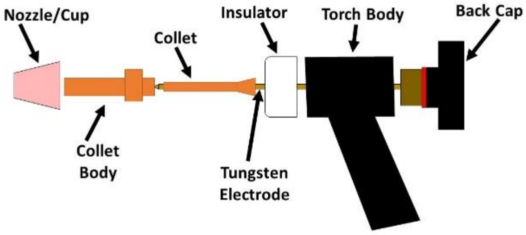

Figure 2. TIG torch component diagram.

Figure 3. Original location of the back cap.

In this paper, the objectives were met by selecting a compact torch and redesigning the end-effector as well as developing a novel method to change out electrodes. These objectives were established to improve the productivity and reliability of the system and to maximize the printing envelope of the mBAAM system. The following sections demonstrate the approach for the end-effector and the ECS design, the controls and interaction between the robot and the ECS, and the results of the final system. The final products (Fig. 4) were developed by a team of students from the University of Tennessee as a senior design project. This led to prototypes that were used to analyze mBAAM system improvements.

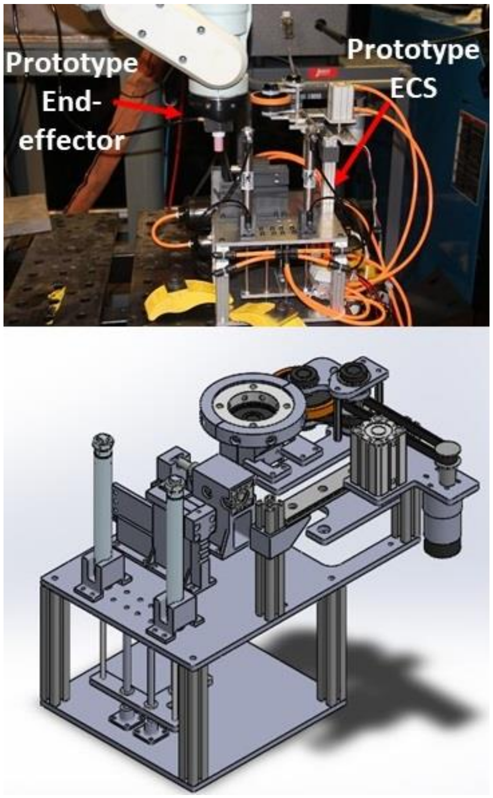

Figure 4. The real prototype design on the PA10 mBAAM system (top) and the CAD prototype model of the torch end-effector interfacing with the ECS (bottom).

TORCH END-EFFECTOR DESIGN AND APPROACH

A. *Torch Mounting Design Evaluation*

A shorter torch leads to a shorter end-effector; however, mounting placement can also affect the height of the torch end-effector. There are two mounting methods that can be implemented. The torch head can be mounted either concentric or off-center to the robot arm wrist (Fig. 5). For example, Lincoln Electric implemented an off-center TIG torch mount on a Fanuc robot [11], while a concentric mounting was used for the ABB TIP TIG robot [12].

An advantage to using an off-center design is its suitability for wire feeding. The offset can be set in a position where the wire extrudes directly to the work object. Because AM requires printing layer-by-layer, this allows a constant wire direction. This is beneficial because it potentially stops the wire from curling away from the melt pool, which causes faulty deposition. A disadvantage to using off-center mounting is its effect on the printing parameters and the design of the ECS. An off-center mount could increase the risk of the robot colliding with the work object or itself. Limitations on the rotation of the robot's wrist must be set when the torch body is positioned above the robot's wrist. This limitation prevents the torch body from colliding with the robot arm. Limiting maneuverability also causes a reduction in the build envelope. Using an off-center mount can create difficulty with ECS interfacing. An ECS needs to be collision free and accessible for the torch. Since the arm and torch coordination systems are different because of the offset, complex robot paths are needed to properly interface with the ECS. This likely leads to redundant robot movements to ensure the robot and/or the torch end-effector do not collide with the ECS. Extra movement increases the time spent not printing, reducing productivity.

A concentric mount can be treated as a vertical extension of the robot's wrist. This allows the torch-end effector to have the same coordinate system of the robot thus avoiding potential path redundancies. The disadvantages of using this mounting style are the extended length and wire feed alignment. However, the acquired compact torch and adjustable wire guide permitted selection of the concentric mount.

Figure 5. Torch mounting configuration based on off-center (left) or concentric (right) alignment with the robot wrist. The welding robots pictured are a Fanuc Arc mate robot (left) and a ABB TIP TIG robot (right) [7],[8].

B. *Prototype Design and Hardware*

Fig. 6 shows the CAD model of the prototype torch end-effector. The development of the new torch end-effector was dependent on the hardware that was selected and the method of interfacing with an ECS. The hardware consisted of:

- Compact torch: CK Worldwide MT-400
- Wire guide: CK Worldwide 3-WGBX-60
- Back Cap: small back cap with rubber wheel
- Torch Housing: 3D printed out of ABS for prototype

The compact torch was a key component to decreasing the length of the end-effector while using a concentric mount. To properly select a torch, it had to be similar to the previous torch used on the mBAAM system. The old torch had a welding AC current capacity of up to 300 A at 100% duty cycle. The new torch required a minimum current of 300 A at 100% duty cycle to properly replace the old torch. Printing large parts can take many minutes per layer. Large parts also require the torch to run for prolonged periods of time. Water-cooling is a necessity to keep the torch from overheating during usage. The selected torch, MT-400, met all the requirements, as it had a max 100% duty cycle of 400 A with water-cooling. The total length of the torch is about 83.8mm, which is highly compact compared to the standard length of 229mm long.

The wire guide was selected from the same distributor. It can position the wire feed direction in multiple degrees of freedom. This manipulation is necessary to accommodate the direction of the weld, which is crucial for smooth deposition. According to Geng et al., wire feeding placement was considered an important variable in their deposition optimization process [8].

The small back cap was purchased with the torch. Modification was done to properly interface with the prototype ECS. A rubber wheel with a diameter of 60.3 mm and thickness of 10.2 mm was press fitted into the back cap with a knob thickness of 7.62 mm. The bottom face of the wheel was flush with the bottom face of the back cap's knob (Fig. 6). The wheel's diameter provided an easier access to rotating the back cap while staying within the robot wrist's 98 mm diameter. The selected rubber wheel provided an economical, easy interface solution.

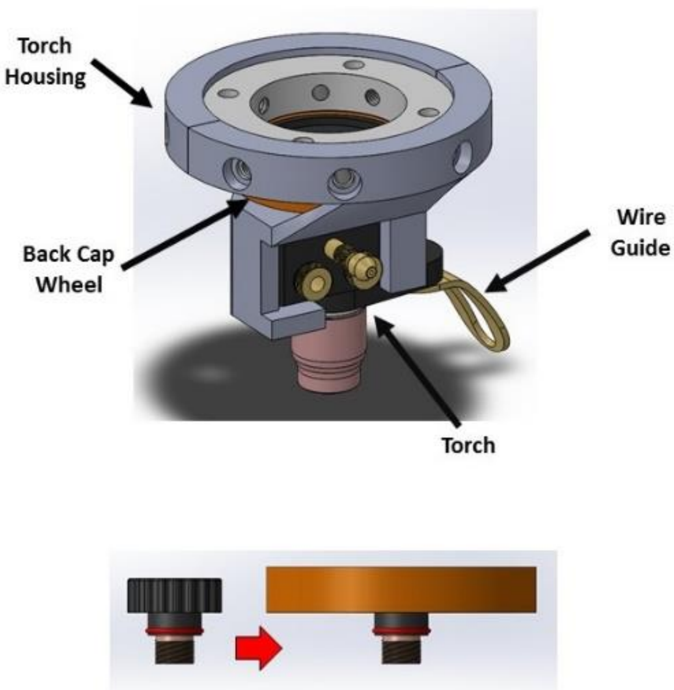

Figure 6. CAD model of the prototype torch end-effector (top) and a CAD model of the wheel attachment on the back cap (bottom).

The torch housing that holds all the components were 3D printed out of ABS plastic. The old housing was also 3D printed using the same material and was stable during operation. 3D printing the torch housing also reduced the weight of the end-effector, which satisfies one of the objectives. An aluminum plate was used to hold the housing together and mount onto the wrist. This housing had cutouts that provided access to the gas and water lines of the torch and to the back cap wheel. The total length of the new end-effector was 98mm, a drastic decrease in length compared to its predecessor (267 mm). Fig. 7 shows the visual difference of size.

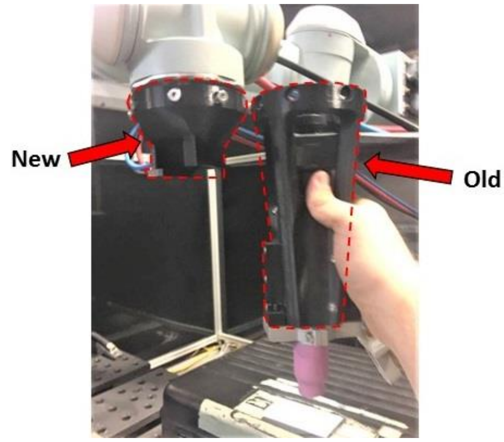

Figure 7. An image of the new and old torch end-effector beside each other.

ECS MECHANICAL DESIGN AND APPROACH

This section describes the functionality and the design approach of the prototype ECS. Since electrode changing is a multi-step process, subsystems/units had to be developed. All units were compacted into a single system, allowing it to fit in a minimum volume of 304 x 305 x 332 mm.

A. Torch Back Cap Interface Unit

Traditionally, a back cap is manually turned to loosen or clamp onto the tungsten electrode. Clamping is achieved when the back cap screws into the torch, pushing a collet inside the torch body. This pushing force compresses the collet, which results in clamping an inserted electrode. The back cap is not necessarily required for collet compression. One method developed by Tokinarc is to remove the back cap and replace it with a pneumatic actuator [13]. This integrated actuator pushes onto the collet allowing electrode clamping and unclamping. Minimizing the length and mass of the end-effector were some of the objectives mentioned in Section I of this paper. Attaching an actuator to the back of the torch would lead to the opposite. As mentioned in Section II-part B of this paper, the back cap was kept, but it was modified by fitting a wheel to it. A friction drive mechanism on the ECS was the approach used to interface with the back cap wheel. This unit is shown in Fig. 8.

The friction drive uses a two-stage belt transmission to drive a 73mm diameter wheel. This is powered by a 12V 100:1 geared DC motor. The housing for the wheel is designed to hold the wheel and the second staged belt. Bearings are used on the pulley side of the housing to enable free rotation on that pivot, while also driving the wheel. The purpose to this design is to keep the motor from becoming an obstacle to the robot as well as keeping the ECS compact. Using surgical tubing, tension is applied to ensure compression between the back cap wheel and the drive wheel when the robot positions to the interface. Surgical tubing was selected for its durability, and it was inexpensive. This compression allowed the back cap wheel to be driven without the issue of slipping. As the robot interfaces with the drive wheel, the wheel housing would cock back as force was applied to it. This prevented the robot from stopping due to a force sensor limit. Once the torch end-effector wheel was in full contact with the drive wheel, the back cap can turn to loosen or tighten an electrode.

The friction drive is also capable of translating to fixed positions: one for interfacing and one for electrode loading. This is achieved by using the interface plate that holds both the motor and wheel housing and attaching a linear slide to it. To prevent this plate from moving while the robot is interfacing with the friction drive, a pneumatic actuator is placed on the interface plate. When the actuator extends, it inserts through a hole, cut into another plate attached to the linear guide rail. The actuator can also push against the surface of this plate, acting like a friction brake.

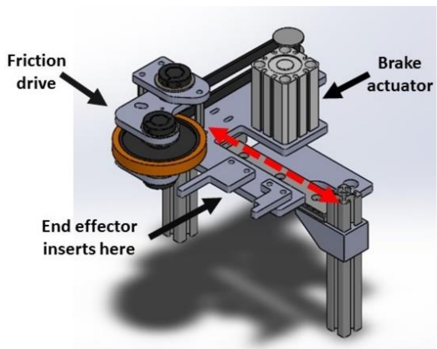

Figure 8. CAD model of the interface unit with depiction of its translating motion.

The position of the back cap interface unit is driven by the robot. Two small blocks are fastened to the interface plate. The end effector is placed between the two blocks. These blocks act as walls that the robot pushes to drive the back cap interface unit. This simplifies the ECS's design and controls by only depending on the positional controls of the robot. Since the robot drives it, this eliminates the need for an additional mechanism to drive the back cap interface unit.

B. *Electrode Removal Unit*

Loosening the back cap does not guarantee the electrode from dropping out of the torch. The electrode can be slightly warped, deformed, and or have a rough surface that would prevent the electrode from sliding off naturally. The robot could be taught to shake itself to remove the electrode; however, this method would be physically impractical for the arm. A practical method would be a mechanism that can assist the removal of the electrode.

The electrode removal unit (Fig. 9) consists of a pneumatic actuator and a wall. The main plate that holds all the units together has a hole for an electrode to drop in. Electrode removal is achieved when the back cap is in unclamping position, and the robot arm is positioned between the wall and the actuator. For proper gas shielding, the electrode sticks out of the cup of the torch. The stick-out allows the actuator to push the electrode against the wall. This clamps the electrode in place, and the robot moves up to fully remove the electrode. The used electrode will then drop through the hole of the plate.

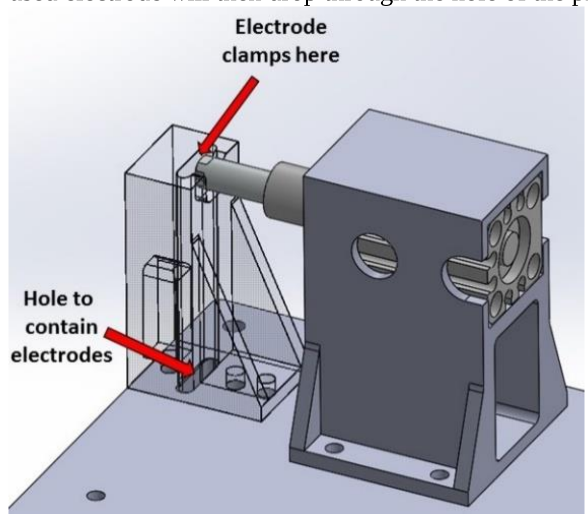

Figure 9. CAD model of the electrode removal unit.

C. *Electrode Loading Unit*

The development of the electrode loading unit was a challenging part of the design (Fig. 10). To improve the productivity and reliability of the mBAAM system, the loading unit must hold enough electrodes to build a large part and must consistently load individual electrodes into the torch. Having the electrode load at the same position can reduce the travel-time of the robot arm and save time. An alignment of stationary electrodes, which is another possible solution, would require the robot to vary in position per change out. No alternative solution to electrode loading was discovered from researching the topic. This resulted in exploring tool changing systems used in robot automation.

Ryuh et. al. implemented a method for automated robotic polishing using a rotary indexer with multiple polishing tool heads [14]. By replacing the tool heads with electrodes, an initial approach was developed. However, this approach was impractical. Although cost was not one of the key objectives of this work, a cost-effective, reliable system is more desirable. A high precision rotary indexer may have some advantages but is costly. To hold electrodes, a separate plate must be machined and attached to the indexer. Additional machining costs adds to the total cost of the system. To prevent electrodes from colliding with the end-effector and/or robot, electrodes must be spaced. Using multiple electrodes results in the need for a large plate. A large build plate either reduces the building envelope of the mBAAM system or positions the ECS in a far-reaching location. Implementing this approach with the prototype end-effector design would be the most difficult. A torch with an active clamping mechanism can grab an electrode, contact the electrode's tip on a flat surface, and then adjust the protrusion length of the electrode by unclamping the electrode and having the torch lower down [13]. However, the prototype torch-end effector does not have a clamping mechanism and cannot adjust the electrode using that method. Having a long electrode pultrusion would reduce the effectiveness of the gas shielding the electrode [15], thus complicating the matter of keeping the electrodes stable while indexing. These multiple complications led to the development of an innovative approach to electrode loading.

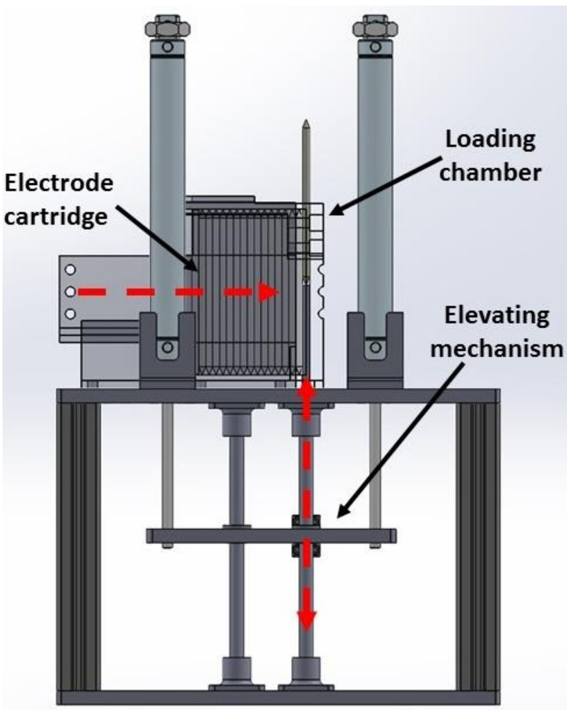

Figure 10. The electrode loading unit with depiction of the motion for the cartridge and elevating mechanism.

Comparable to a gun magazine or cartridge, an elastically driven mechanism indexes the electrodes. The cartridge components are mostly comprised of 3D printed parts. 3D printing was chosen for rapid prototyping. This was useful, as some changes to the cartridge were required because of electrodes jamming in the early design. The cartridge had a capacity of 16 electrodes and was loaded from the top. For the selected torch described in this paper, the electrodes were 76.2mm in length and 3.2mm in diameter. A cover was placed at the top of the cartridge to prevent electrodes from popping out. Surgical tubing pulled the pusher mechanism, which forced the electrodes into the loading chamber. Rubber bands were initially used, but they often broke. The loading chamber mechanism used two pneumatic actuators to pull out and push in a guided rod plate to elevate an electrode. A single actuator was initially used but resulted in binding the guided rod plate and jamming the elevation system. A steel rod with the same diameter as the electrode was attached to the guided rod plate. The rod was then used to push out an electrode, where the rod was flush with the top surface of the loading chamber block when fully extended. The mechanism was configured this way to minimize the height of the ECS.

ROBOT AND ECS CONTROL PLANNING

A. Robot Path and Controls

The PA10 robot was programmed using National Instruments LabVIEW software, and an in-house LabVIEW-based human machine interface (HMI) was developed [9]. Parameters, such as the position, joint angle, and arm speed, can be changed without the need to reprogram the robot controller. This allowed real-time robot movement by simply entering coordinate points. While developing the ECS, it was determined that the PA10 must travel to a minimum of four coordinate points to complete electrode changeout. These points mainly correlate with the location of the separate units in the ECS. The four points are:

- Home: This is the start position to begin interaction with the ECS. When an electrode has been changed, this becomes the end position.
- Interface: This is where the torch end effector docks into the back cap interface unit.
- Load: This is where an electrode loads in the torch
- Removal: This is the point where an electrode is removed.

These four points are close to each other; the greatest distance between any of the points was 152 mm. To reduce travel time spent interfacing with the ECS, only these four points were used. This was achieved by only using linear paths to travel to these points as seen in Fig 11. Manual control of the PA10 was used to examine the interaction between the arm and the ECS. Proper location of these points were obtained from this study. Using these points, a semi-autonomous program was developed in LabVIEW to run through these paths sequentially. The purpose of using a semi-autonomous system was to analyze prototype interface capabilities between the robot and the ECS.

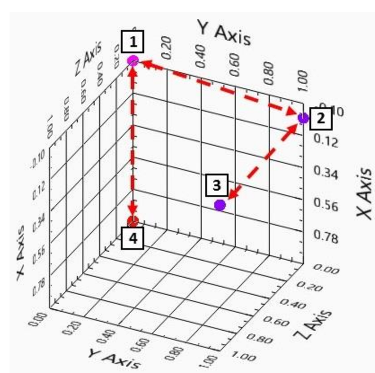

Figure 11. 3D graph of the robot's path with the home (1), interface (2), load (3), and removal (4) points.

B. ECS Control System and Synchronization Procedure

The control system consisted of these devices:

- Arduino Uno microcontroller: Programmed to control the motor controller and the relay board

- Motor controller: Changes the direction and speed of the motor that is used on the friction drive mechanism
- 4-channel relay board: Three relays are used in the board to individually power three solenoid valves that drive the actuators

LabVIEW was used to program the Arduino. Virtual controls were designed using LabVIEW's front panel (HMI) and was then installed on a computer to interface to the Arduino. The front panel has two tabs to switch from manual or semi-autonomous mode as seen in Fig. 12. Manual mode is used to individually control the units used in the ECS. This was mainly for analyzing the ECS's performance; however, it was also used for calibrating the interaction between the PA10 and the ECS. The full control system is shown in Fig. 13. The semi-autonomous mode had a similar setup to the one used for the PA10 but with more automation.

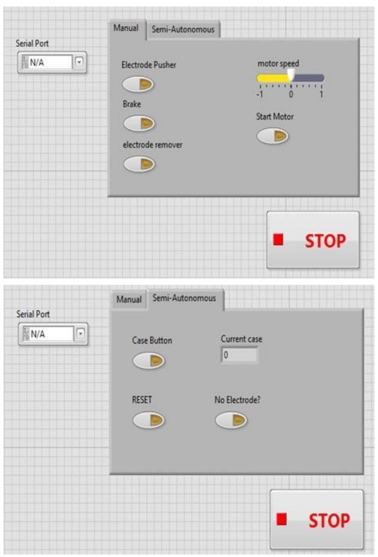

Figure 12. LabVIEW front panel with both manual (top) and semi-autonomous modes (bottom) used to control the ECS

Synchronization for the prototype was achieved by having one person control the robot, while another person controls the ECS. The robot operator led the interfacing procedure because the ECS controls were heavily dependent on the robot's path. By adding the semi-autonomous controls to both systems, this operation was easy to maneuver. The robot operator stepped through the semi-autonomous program used for the robot, keeping track of the robot's position. The robot operator then notified the ECS operator of the positional state of the robot. To help assist this operation, both programs displayed what step has been executed. A flow chart of these executed steps is shown in Fig.14.

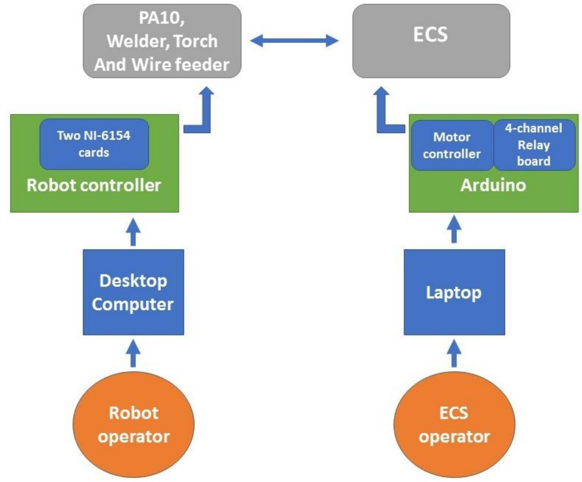

Figure 13. Control system of the combined system (mBAAM & ECS).

Semi-autonomous control was not an ideal process, but it was the fastest method to test the functionality of the prototype design integrated into the mBAAM system. Full automation can easily be implemented by replacing the laptop used to control the Arduino with the main robot controller.

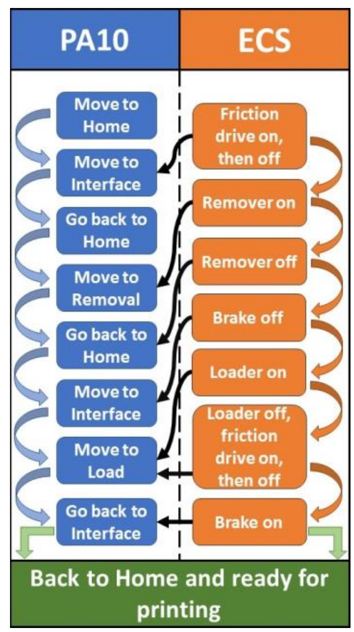

Figure 14. Full system flow chart on electrode changeout process

SYSTEM RESULTS

Each robot interaction with the separate units of the ECS was observed. Interaction between the interface unit and torch end-effector attached to the robot was successful. Despite some minor flexing when docking occurred, no collision errors occurred on the robot. The ECS also worked consistently well. On the back cap interfacing, the friction wheel successfully turned the back cap wheel. Through observation, an electrode was still capable of falling out without interfacing with the removal unit. Although it rarely happened, this occurred when loosening the back cap. This slightly interfered with the change out process in terms of redundant robot movement. By adding a proximity sensor at this location, electrode detection was established and programmed to skip redundant robot travel. An issue that did occur was when the friction drive was manually controlled to loosen the back cap. Due to the high torque of the motor, the drive wheel turned the back cap wheel too much, jamming it to the robot end. The end-effector had to be taken apart from the robot to unjam it. This issue was temporarily solved by stopping the rotation of the back cap wheel through timed operation; however, a simple permanent solution is to read the current on the friction drive to stop motion when the limit is reached.

Interfacing with the removal unit was mostly successful. However, the robot must fully move back to the home point with the electrode clamped for successful removal. When the electrode interfaced with the clamping actuator, it would bend the electrode inside the torch. If the electrode was released before reaching to the home point, the electrode would stay in the torch from the bending. At home point, the electrode is no longer in contact with the torch. This prevented the electrode from staying in the torch. Human error was the main cause of this error, and it can be easily fixed in a fully synchronized automated process.

To test for any failures, the PA10 repeatedly moved the back cap interface unit back and forth. No source of robot collision errors occurred during this testing. The PA10 kept its position, perfectly aligning with the electrode loading unit. The electrode loading process was highly reliable. Prior to robot and ECS interaction, the ECS's loading unit was tested for electrode jamming. The loading unit managed to empty out five fully-loaded cartridges (80 electrodes) consecutively without failure. When testing it with the robot, The ECS successfully loaded in an electrode and properly tightened the back cap with no failure throughout the whole testing campaign.

CONCLUSION

Improvements were desired to increase the productivity, reliability, and build volume of the mBAAM system. Design objectives for a new torch end-effector and ECS were met and implemented for the mBAAM TIG system. The end-effector length was reduced 63% in length when compared to the old end-effector. The ECS design was successful in replacing electrodes. Through semi-autonomous controls, electrode change out time took less than 45 seconds. Full automation of the system would likely lead to a complete electrode change out in less than 15 seconds.

ACKNOWLEDGMENTS

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Energy Efficiency & Renewable Energy, Advanced Manufacturing Office, under contract number DE-AC05-00OR22725. This material is also supported by the University of Tennessee, Knoxville's Department of Mechanical, Aerospace, and Biomedical Engineering.

REFERENCES

[1] I. Gibson, D. Rosen and B. Stucker, Additive Manufacturing Technologies, New York: Springer , 2010.

[2] A. Nycz, A. I. Adediran, M. W. Noakes and L. J. Love, "Large Scale Metal Additive Techniques Review," in *Solid Freeform Fabrication Symposium - An Additive Manufacturing Conference*, Austin, 2016.

[3] W. E. Frazier, "Metal Additive Manufacturing: A Review," *Journal of Materials Engineering and Performance,* vol. 23, no. 6, pp. 1917-1928, 2014.

[4] D. Ding, Z. Pan, D. Cuiuri and H. Li, "A multi-bead overlapping model for robotic wire and arc additive manufacturing (WAAM)," *Robotics and Computer-Integrated Manufacturing,* vol. 31, pp. 101-110, 2015.

[5] J. Ding, P. Colegrove, J. Mehnen, S. Ganguly, P. S. Almeida, F. Wang and S. Williams, "Thermo-mechanical anaysis of Wire and Arc Additive Layer Manufacturing process on large multi-layer parts," *Computational Material Science,* vol. 50, no. 12, pp. 3315-3332, 2011.

[6] P. S. Almeida and S. Williams, "Innovative process model of Ti–6Al–4V additive layer manufacturing using cold metal transfer (CMT)," in *Proccedings of the 21st Annual International Solid Freeform Fabrication Symposium*, Austin, January 2010.

[7] F. Wang, S. Williams and M. Rush, "Morphology investigation on direct current pulsed gas tungsten arc welded additive layer manufactured Ti6Al4V alloy," *The International Journal of Advanced Manufacturing Technology,* vol. 57, no. 5-8, p. 597, November 2011.

[8] H. Geng, J. Li, J. Xiong, X. Lin and F. Zhang, "Optimization of wire feed for GTAW based additive manufacturing," *Journal of Materials Processing Technology,* vol. 243, pp. 40-47, 2017.

[9] A. Nycz, M. W. Noakes and L. J. Love, *Control Strategies for Large-Scale Additive Manufacturing,* Austin: National Instruments, 2017.

[10] L. B. Gueta, R. Chiba, T. Arai, T. Ueyama and J. Ota, "Design of the end-effector tool attachment for robot arm with multiple reconfigurable goals," in *2008 IEEE International Conference on Automation Science and Engineering*, Arlington, 2008.

[11] "Robot Peripheral Equipment Product Information│Tokin Corporation welding torch, tip, robot torch, fume collectors, manufacture and sale of environmental equipment, optical components sales," Tokin Corporation, 2017. [Online]. Available: http://www.tokinarc.co.jp/english/goods/7_index.html#series42. [Accessed 15 9 2017].

[12] G. Lipnevicius, "Welding Design & Fabrication," 27 July 2010. [Online]. Available: http://weldingdesign.com/equipment-amp-automation/does-robotic-tig-welding-make-sense-your-company. [Accessed 15 9 2017].

[13] T. Heston, "The Fabricator," 6 September 2009. [Online]. Available: http://www.thefabricator.com/article/arcwelding/robotic-gtaw-or-gmaw-no-longer-a-clear-cut-choice. [Accessed 15 9 2017].

[14] B.-S. Ryuh, S. M. Park and G. R. Pennock, "An automatic tool changer and integrated software for a robotic die polishing station," *Mechanism and Machine Theory,* vol. 41, no. 4, pp. 415-432, 2006.

[15] K. Weman, "TIG welding," in *Welding process handbook*, Woodhead Publishing Ltd , 2003, pp. 31-36.